

LABORATORY ILLUSTRATIONS OF THE TRANSFORMATIONS AND DEPOSITION OF INORGANIC MATERIAL IN BIOMASS BOILERS

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ABSTRACT

Boilers fired with certain woody biomass fuels have proven to be a viable, reliable means of generating electrical power. The behavior of the inorganic material in the fuels is one of the greatest challenges to burning the large variety of fuels available to biomass combustors. Unmanageable ash deposits and interactions between ash and bed material cause loss in boiler availability and significant increase in maintenance costs. The problems related to the behavior of inorganic material now exceed all other combustion-related challenges in biomass-fired boilers. This paper reviews the mechanisms of ash deposit formation, the relationship between fuel properties and ash deposit properties, and a series of laboratory tests in Sandia's Multifuel Combustor designed to illustrate how fuel type, boiler design, and boiler operating conditions impact ash deposit properties.

INTRODUCTION

Biomass-fired electric power generating stations are assuming increasingly prominent positions in energy and environmental issues in many regions of the world [Hustad and Sønju, 1992]. Such power stations typically are small (less than 50 MW_e net output), and rely on indigenous fuel supplies. Fuels for such facilities can be broadly classified into the categories of wood, agricultural residues, urban and municipal waste, and energy crops. Wood commonly represents the fuel of choice and the design fuel for biomass power stations. Wood's use is limited by availability, cost, and permitting agreements but in most cases not by fireside related problems (fouling, slagging, corrosion, etc.) in the boiler. The cost of wood fuel for such power stations in recent years was impacted by competition among the biomass power stations in some regions of the US, although such competition has waned in the last 18 months. At its peak, the cost of wood fuel in Northern California (USA) increased by over a factor of two from its baseline value prior to significant biomass combustion demand [Turnbull, 1993]. The availability of wood is beginning to decrease as a result of substantial reductions in logging associated with economic policy and wildlife protection. The probability of high fuel prices and unreliable availability motivate evaluation of new fuels for these combustors.

The motivation to develop new fuels for some power stations is driven by regulation and legal agreements more than by economics or availability. For example, under Title I of the U.S. federal Clean Air Act Amendments of 1990, states designate areas within their boundaries as attainment, non-attainment, or unclassifiable for each of six pollutants [1989]. Designations are based on either federal or state air quality standards. Operating permits for all biomass-fired power stations are based in part on their impacts on air quality. For power stations in or near non-attainment areas, permits often require a net *reduction* in the amount of pollutant (NO_x, particulate matter, etc.) generated in that area. This is accomplished by use of offset fuels, that is, fuels that would otherwise be burned in the field and produce higher levels of pollutants than what is produced if the same fuels are burned in a boiler. Agricultural byproducts generally and straw in particular represent common examples of offset fuels. Some power stations agree in their permits to consume sufficient offset fuel that they compensate for the pollutants produced from their overall operation, resulting in a net decrease in pollution as a result of operating the power plant.

Economic, long-term-planning, environmental, regulatory, and legal motivations can be strong for using offset or alternative fuels in biomass combustors. In addition, large and reasonably stable supplies of these fuels can be secured in many regions of the country. In practice, combustion of these fuels has proven difficult. Problems vary from fuels handling and storage to seasonal variations in both the amount and the quality of the supply. Arguably the most daunting issue, and the subject of this investigation, is the inorganic material in the fuel and its impact on the combustor. For example, essentially all biomass-fired power stations in

California that were designed and permitted based on using straw as an offset fuel opt to process straw by means other than combustion. These decisions are driven by the consistent experience of unmanageable bed agglomeration, slagging deposits, and convection pass fouling when burning straw. Several international studies have been completed in the general area of straw combustion [FEC Consultants Ltd., 1988; Livingston, 1991; Martindale, 1982; Martindale, 1984]. In many cases, addition of as little as 10 % straw to the boiler fuel supply for an electric power-generating facility causes an unscheduled shutdown within a few hours. Field experience with some other offset or alternative fuels (orchard prunings, nut shells or hulls, fruit pits, etc.) demonstrates borderline operation, with blend ratios limited to only 10-15 % when fired with wood [Miles, 1992; Miles and Miles, 1993; Miles, et al., 1993].

General mechanisms of ash deposition and laboratory/pilot-scale tests of bed agglomeration during straw combustion are discussed elsewhere [Baxter, 1993; Salour, et al., 1993]. The current investigation combines laboratory and field data in examining the causes of fireside problems during biomass combustion in a mechanistic way. Laboratory tests were conducted in a pilot-scale combustor and incorporated both *in situ* and *post mortem* analyses of ash deposit morphology, composition, and rate of accumulation. In separate reports, the details of an extensive series of laboratory and field tests of over a dozen biomass fuels and their ash-related combustion behaviors are discussed [Baxter, et al., 1995; Jenkins, et al., 1994; Miles, et al., 1994]. These sets of data are analyzed both separately and in comparison to demonstrate several of the most important aspects of ash behavior during straw combustion. This paper summarizes the laboratory findings during these investigations and illustrates many of the issues associated with the ash behavior of biomass fuels.

FACILITIES

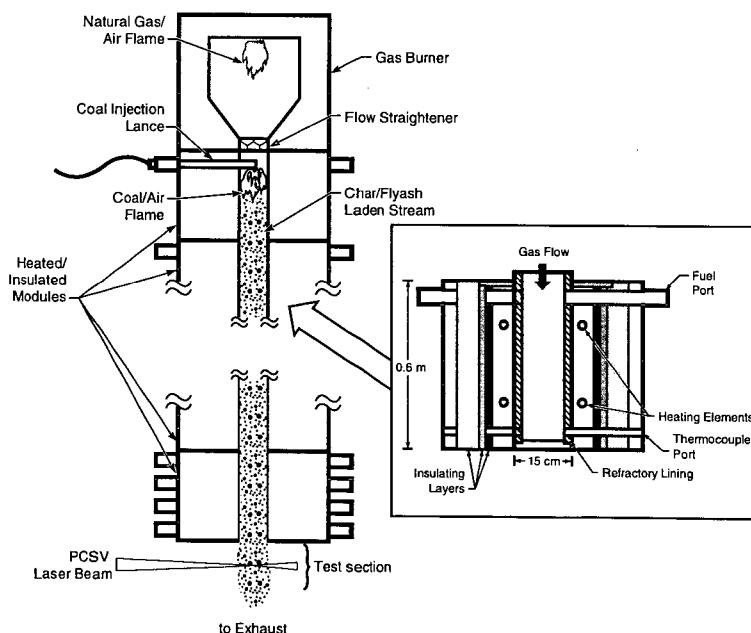


Figure 1 Schematic diagram of the Sandia Multifuel Combustor used in these combustion tests with modular guard heater inset.

The Multifuel Combustor (MFC) at Sandia was used to perform laboratory- and pilot-scale tests on ash deposition during combustion of the solid fuels indicated in Table I. The MFC is a pilot-scale (30 kW) down-fired, turbulent flow reactor that simulates the gas temperature and composition histories experienced by particles in combustion systems (Figure 1). A gas burner is used to provide a vitiated air to the remainder of the combustor. Gases from the burner flow through a series of modular sections that include guard heaters, fuel insertion ports, and thermocouple insertion ports. At the end of these modular heaters is the test section of the combustor. In this section, several air-cooled deposition surfaces that simulate waterwalls and convection pass tubes are injected in the particle-laden, vitiated flow. In the experiments described here, surface temperatures of these tubes are measured using thermocouples. Surface

temperature was held constant in each individual experiment but varied from 350 to 650°C among the several experiments performed. Further details about the MFC are available in the literature [Baxter, 1993].

Table 1 Biomass Fuels Tested in Sandia's Multifuel Combustor

Fuel	Moisture (% fuel)	Ash (% dry fuel)	Higher Heating Value (MJ/kg, daf)
Herbaceous Fuels			
Rice Straw	11.22	19.17	18.74
Wheat Straw	8.39	8.08	19.31
Switch Grass	12.98	5.86	19.91
Ligneous Fuels			
Almond Shells	7.52	2.87	19.83
Pistachio Shells	8.08	1.28	19.90
Olive Pits	6.97	1.83	21.97
Almond Hulls	8.02	5.75	20.00
Humus	12.51	34.64	12.89
Commercial Fuels			
Urban Wood Fuel Blend	8.62	7.54	19.97
Nonrecyclable Paper	5.95	8.21	23.44
Wood/Straw Blend	9.25	7.33	20.56

The MFC was designed to simulate conditions in a coal combustor and has nominal fuel residence times of up to about four seconds. Typical fuel residence times in pulverized coal combustors are about two seconds. In the biomass tests, fuels were comminuted, typically to sizes less than 1 mm. This provided for nearly complete carbon conversion of the straws within the maximum residence time available in the combustor.

In all straw combustion tests, fuel was inserted into the MFC at a height of approximately 4.3 m (14 ft.) above the beginning of the test section. Ash deposits were collected from a simulated water wall and convection pass tube as well as from the internal ceramic liner of the MFC.

RESULTS AND DISCUSSION

Alkali metal behavior, in particular potassium, was identified at the beginning of the investigation as a concern. Traditional clean wood fuels contain little ash (< 1 %), and the ash contains relatively small amounts of potassium (5-20 %). The two commercial wood fuels indicated in Table 1 contain less clean sources of wood (urban wood waste, for example) and are blended with other, high ash fuels. The dominant ash components of clean wood include silicon and aluminum. Less traditional fuels, including essentially all of the nonprocessed herbaceous fuels and most of the nonprocessed agricultural residues, contain much more ash (Table 1) and higher potassium concentrations. Processed fuels, such as bagasse from sugar cane, often have very low alkali contents. The behavior of alkali is highlighted below (Figs. 2-4).

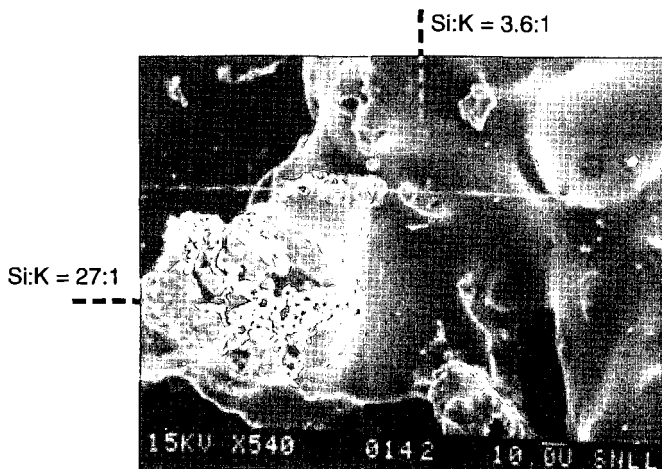


Figure 2. Elemental composition of different regions of a straw ash deposit.

Alkali materials in many forms are slightly volatile under combustion conditions. The resulting inorganic vapors react with other fuel or ash components to exacerbate ash deposition problems by two primary mechanisms. The first mechanism is the formation of molten deposits, an example of which is seen in Fig. 2. The silicon to potassium ratio of two regions of a straw deposit are indicated. The molten region has a silicon to potassium ratio of less than 4:1, whereas the same ratio in the granular region is over 25:1. Alkali metals generally decrease the melting point of silica by formation of alkali silicates. Potassium, the primary alkali metal in biomass, is more mobile during combustion than is common in, for example, coal. This leads to formation of soft or molten deposits for many nontraditional biomass fuels at lower temperatures than is common for coal or traditional woods.

The second mechanism of alkali metals contributing to ash deposition during biomass combustion is the formation of sulfated compounds. The low temperatures of steam tube surfaces promote the condensation of alkali vapors on surfaces. At surface temperatures, alkali sulfates are stable chemical species. The formation of an alkali sulfate layer of the deposit in intimate contact with the surface leads to the formation of a tenacious deposit. This is illustrated in Fig. 3, where the composition of an ash deposit was measured at the deposit crown, in the center of the deposit, and at the probe surface (positions A, B, and C, respectively). The concentration of sulfur monotonically increased as the measurement point approached the probe surface, with the ratio of sulfur at position C being over twice as high as at point A.

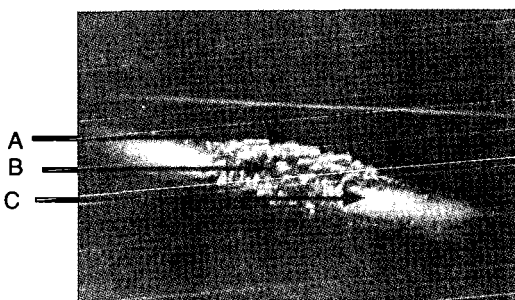


Fig. 3. Illustration of the formation of a sulfate bonding layer in a wheat straw deposit.

Similar behaviors are noted in the field experiments, as indicated in Fig. 4. The analysis compares the composition of the fuel ash and a deposit collected from a furnace surface that experiences little direct impaction of particles. The amount of direct particle impaction on a surface depends primarily on boiler design. This deposit was collected from the wall opposite the furnace exit and convection pass entrance, where particles are directed away from the wall and into the convection pass. Very few impact on the boiler surface in this region. The vapors, on the other hand, are carried with the gases to the wall where they condense and react to form sulfates. As can be seen, the deposit composition is highly enriched in alkali metals and sulfur compared to the fuel ash composition. If boiler design or operating conditions change such that there is greater impact of particles in this region, the composition silica and other species associated with particles increases.

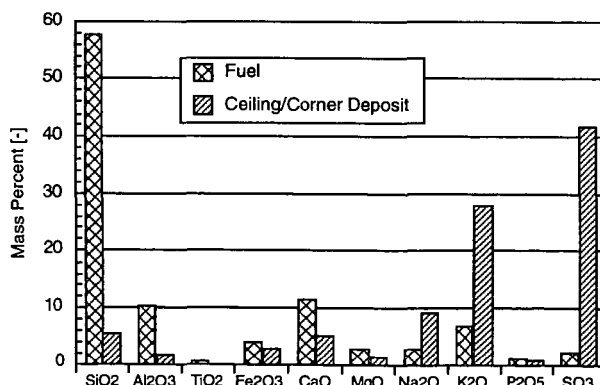


Fig. 4. Comparison between elemental composition of the fuel ash and a thin layer of reflective ash deposited on the ceiling and upper corner of the furnace. All compositions are expressed as oxides.

CONCLUSIONS

A series of laboratory and field tests illustrate the principal mechanisms of ash deposit formation during combustion of biomass fuels. Relationships among the amount and mode of occurrence of inorganic material in the fuel, boiler design, and boiler operating conditions that influence the type of ash deposit formed are discussed. Specific examples of ash deposit formation during combustion of straw are used to illustrate the mechanisms.

Important attributes of ash deposits are determined by the relative rates of particle impaction on surfaces, condensation, and chemical reactions. Deposit morphology, composition, tenacity, porosity, and reflectivity are influenced by the mechanism of deposition. For a specific fuel, the dominant deposition mechanisms vary with location in the boiler and with boiler operating conditions.

Distinguishing characteristics of biomass combustion include the large amount of silica and vaporizable alkali in the ash of nontraditional fuels and the tendency of the silica and alkali to combine chemically on heat transfer surfaces. Alkali vapors condense on cool surfaces to form thin, reflective, alkali-based deposits. The alkali chemically combines with sulfur to form sulfates. In regions where silicon-based fly ash particles accumulate on surfaces, alkali combines with the silica to form silicates. These alkali-silicates have melting temperatures near or below the prevailing gas temperatures. This leads to sintering and formation of molten phases in the deposit. The rate of sintering depends on both deposit temperature and the amount of alkali in the gas phase.

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